Episodicity within a mid-Cretaceous magmatic flare-up in West Antarctica: U-Pb ages of the Lassiter Coast intrusive suite, Antarctic Peninsula and correlations along the Gondwana margin

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**ABSTRACT**

Long-lived continental margin arcs are characterized by episodes of large volume magmatism (or flare-ups) that can persist for ~30 Myr, before steady-state arc conditions resume. Flare-up events are characterized by the emplacement of large volume granodiorite-tonalite batholiths and sometimes associated rhyodacitic ignimbrites. One of the major flare-up events of the West Gondwana margin occurred during the mid-Cretaceous and was temporally and spatially associated with widespread deformation and Pacific plate reorganization. New U-Pb geochronology from the Lassiter Coast intrusive suite of the southern Antarctic Peninsula identifies a major magmatic event in the interval 130 – 102 Ma and is characterized by three distinct peaks in granitoid emplacement at 130 – 126 Ma, 118 – 113 Ma and 108 – 102 Ma, with clear lulls in between. Mid-Cretaceous magmatism from elsewhere in West Antarctica, Patagonia and New Zealand also feature marked episodicity during the mid-Cretaceous and record remarkable continuity along the West Gondwana margin. The three distinct magmatic events represent second-order episodicity relative to the primary episodicity that occurs on a Cordillera scale and is a feature of the North and South American Pacific margin. Flare-up events require the development of a highly fusible, lower crustal layer resulting from the continued underplating of hydrous mineralogies in the melt-fertile lower crust as a result of long-lived subduction. However, the actual trigger for melting is likely to result from external, potentially tectonic factors, e.g. rifting, plate reorganization, continental breakup, mantle plume.

**Introduction**

The mid-Cretaceous is recognised as a period of enhanced global magmatism, tectonic activity and paleo-environmental change (Larson, 1995; Matthews et al., 2012). Several episodes of large igneous province magmatism (oceanic and continental) and extensive deformation around the margins of the paleo-Pacific have been identified during the mid-Cretaceous period (Ernst et al., 2003; Vaughan and Livermore, 2005; Bryan and Ferrari, 2013) coinciding with a period of major global plate reorganization (Matthews et al., 2012) and increased plume-lithosphere interactions (Vaughan, 1995). Along the West Gondwana margin, mid-Cretaceous (Vaughan et al., 2012a) compressional deformation is evident from Patagonia to Marie Byrd Land (Fig. 1a) and is associated with widespread, voluminous plutonism, particularly in Patagonia (e.g. Pankhurst et al., 1999), the Antarctic Peninsula (e.g. Vaughan et al., 2012a), Thurston Island (Riley et al., 2017a), Marie Byrd Land (Siddoway et al., 2005) and New Zealand (Milan et al., 2017).

New U-Pb geochronology is presented here from the Lassiter Coast intrusive suite of the southern Antarctic Peninsula (Rowley et al., 1983); fourteen granitoids have been dated from the entire Lassiter Coast of the southeast of the Antarctic Peninsula and include a lithological range from granite to tonalite to diorite. The selected granitoids exhibit a broad range of deformation fabrics from essentially undeformed to Is-tectonites, and include samples from smaller, isolated plutons as well as larger, composite bodies. They are considered to be representative of the broader intrusive suite both spatially and temporally. The new geochronology is interpreted alongside existing mid-Cretaceous ages from the Antarctic Peninsula, as well as the neighbouring continental blocks of Marie Byrd Land, Thurston Island, New Zealand and Patagonia. The ages are considered alongside the mid-Cretaceous deformation events of the Antarctic Peninsula and any control they had on pluton emplacement.

**Geological Setting**

The Antarctic Peninsula was initially interpreted as an autochthonous continental arc of the West Gondwana margin, which developed during Mesozoic subduction (Suarez, 1976; Pankhurst, 1982). Vaughan and Storey (2000) re-interpreted the evolution of the Antarctic Peninsula as a collage of para-autochthonous and allochthonous terranes accreted onto the West Gondwana margin. The terrane hypothesis has recently been challenged by Burton-Johnson and Riley (2015) who favour a model involving in situ continental margin arc evolution. Rifting in the Weddell Sea during the Middle – Late Jurassic also influenced the geological evolution of the eastern margin of the Antarctic Peninsula (e.g. Jokat and Herter, 2016).

The Mesozoic volcanic and sedimentary successions of the eastern Antarctic Peninsula all have a characteristic continental affinity (Riley and Leat, 1999) and in the northern Antarctic Peninsula they unconformably overlie Carboniferous – Triassic age metasedimentary rocks of the Trinity Peninsula Group (Barbeau *et al.,* 2010; Bradshaw *et al.,* 2012). The Trinity Peninsula Group is estimated to have a thickness of at least 5 km, deposited as submarine fans along a continental margin (Hathway, 2000); it overlaps with, and is likely to overlie Ordovician – Permian age crystalline basement (e.g. Millar et al., 2002; Bradshaw et al., 2012; Riley et al., 2012).

The Mesozoic sequences of the Antarctic Peninsula underwent low- to medium-grade metamorphism and deformation, potentially during the Palmer Land deformation event (116 – 103 Ma; Vaughan et al., 2012b) or during an earlier Late Triassic – Early Jurassic Peninsula deformation event (Storey et al., 1987).

The Early – Middle Jurassic silicic volcanic rocks of the southern Antarctic Peninsula (Palmer Land) include the Brennecke and Mount Poster formations (Riley et al., 2001; Hunter et al., 2006), which form part of the wider first-stage event (V1) of the Chon Aike Province (Pankhurst et al., 2000) and overlap with the voluminous Karoo-Ferrar flood basalt volcanism (Svensen et al., 2012). They are associated with minor basaltic successions (Riley et al., 2016) and extensive shallow marine sedimentary rocks of the Latady Group (Hunter and Cantrill, 2006).

Granitoid plutonic rocks form the most widespread igneous outcrops on the Antarctic Peninsula, occurring as individual plutons, composite intrusions and an extensive batholith constructed during Mesozoic–Cenozoic time (Leat et al., 1995). The paucity of exposure and geochronological-geophysical data across large parts of the Antarctic Peninsula mean that it is not possible to know the full extent and connectivity of many exposed granitoid plutons.

**Antarctic Peninsula Batholith**

The Lassiter Coast intrusive suite (LCIS) forms a component of the far more extensive, dominantly Mesozoic, Antarctic Peninsula batholith which extends for 1350 km along the length of the Peninsula (Leat et al., 1995). The Antarctic Peninsula batholith is dominated (>80%) by calc-alkaline tonalite-granodiorite-diorite (QAP modes) compositions, typical of a continental margin arc (e.g. Waight et al., 1998). It preserves a long-lived plutonic record, from the Ordovician (Riley et al*.*, 2012) until at least 23 Ma (Jordan et al., 2014), although it was largely constructed from the Triassic to the mid-Cretaceous, with major pulses in emplacement correlated to events elsewhere along the proto-Pacific margin of Gondwana (Riley et al., 2017b). A distinct, but widespread plutonic event was identified (Riley et al., 2017b) from the central and southern Antarctic Peninsula and marks the development of a major magmatic event during the construction of the Antarctic Peninsula batholith. A suite of moderate to strongly foliated granitoids (tonalite, granite and granodiorite) that locally form the crystalline basement have been dated in the interval 188 – 181 Ma and overlap with ages from the Subcordilleran plutonic belt of Patagonia (Rapela et al., 2005).

Another significant period of magmatism and extension occurred during the Early Cretaceous and is evident from several sites on the Antarctic Peninsula, but is particularly widespread in northwest Palmer Land (Fig. 1b) at the Wiley Glacier Complex (Wareham et al., 1997). Granitoid compositions of gabbro-tonalite-granodiorite were emplaced at ~141 Ma during an episode of extension (Vaughan et al., 1997). The granitoids were interpreted as fractionates of more mafic material, combined with partial melts of amphibole ± garnet-bearing crust (Wareham et al., 1997). They are typically low-Nd granitoids, which were interpreted to be the result of crustal extension.

The other main episode of Mesozoic pluton emplacement in the construction of the Antarctic Peninsula batholith occurred during the mid-Cretaceous and is the subject of this paper.

**Lassiter Coast intrusive suite (LCIS)**

The LCIS is an extensive suite of individual plutons, composite plutons and batholiths that crop out over a geographical area of 80,000 km2 (Fig. 2) with the intrusions having an aerial extent of 13,000 km2. The plutons are calc-alkaline granitoids and range in composition from granite to gabbro (72 – 51 wt% SiO2), with the majority of the plutons being tonalite-granodiorite in composition (Vennum and Rowley, 1986). The LCIS is associated with mid-Cretaceous subduction along the proto-Pacific margin of West Gondwana (Veevers, 2012). The granitoids are varied in texture from hypidiomorphic to magmatically and tectonically foliated; mafic enclaves are abundant, often forming dense clusters (Fig. 3). The LCIS has traditionally thought to have been dominated by the Werner Batholith, which has an aerial extent of >10,000 km2 (Vaughan et al., 2012a), but recent mapping indicates that the Werner Batholith (Fig. 2) is more likely to consist of multiple smaller plutons with areas of 50 – 3200 km2. Detailed descriptions of the dated samples are provided in the results section.

Several intrusions from the Lassiter and Orville coasts (Fig. 2) have been dated using mostly Rb-Sr and K-Ar whole rock and mineral methods (Mehnert et al., 1975; Farrar and Rowley, 1980; Farrar et al., 1982, and Pankhurst and Rowley, 1991). An age range of 119 – 95 Ma was recorded, but with the peak of emplacement in the range, 110 – 100 Ma. There are only limited U-Pb and 40Ar/39Ar ages published from the LCIS, with Vaughan et al. (2012a) recording 40Ar/39Ar ages of 116.5 ± 1.5 Ma and 107 ± 2 Ma (average of two dates from the same sample) from tonalites sampled from the Beaumont Glacier area (Fig. 2). Flowerdew et al. (2005) have reported a U-Pb age of 105.2 ± 1.1 Ma from a granitoid at Mount Harry on the English Coast (Fig. 1b) which is distal from the main axis of the LCIS, but was considered to form an outlier of the main province. A microgranite dyke, interpreted to also form part of the LCIS, from the central Bean Peaks of the Hauberg Mountains (Fig. 2) was dated (U-Pb) by Vaughan et al. (2002) at 106.9 ± 1.1 Ma. The dyke is intensely cleaved in continuity with the host metasedimentary rocks of the Latady Formation.

The emplacement of the LCIS is temporally and spatially associated with a mid-Cretaceous orogeny, the Palmer Land Event (Vaughan and Storey, 2000; Vaughan et al., 2012a,b), which records two phases of compressional deformation (constrained by 40Ar/39Ar dating; Vaughan et al., 2012a) along the eastern Palmer Land shear zone (Fig. 2). Vaughan et al. (2012b) suggested that the paleostress changes associated with the phase 1 event (~116 – 107 Ma) enhanced magma emplacement and thus was associated with a peak in LCIS magmatism whilst the phase 2 event (~103 Ma) inhibited magma emplacement and was associated with a lull. But they didn’t provide any further details on the precise mechanisms or the duration of the kinematic change. The Palmer Land Event is also interpreted to have imparted a degree of tectonic control on magma emplacement. Smaller plutons (<300 km2) which are more circular in morphology and more rapidly emplaced (<100,000 years) are less likely to preserve any tectonic fabric, whereas larger composite plutons and batholiths (~10,000 km2) are interpreted to have been emplaced over ~10 Myr and are more likely to preserve regional deformation events (Vaughan et al., 2012b).

**Mid-Cretaceous magmatism of West GONDWANA**

The previously published geochronology of mid-Cretaceous magmatism of the southern Antarctic Peninsula has been summarised in the Lassiter Coast Intrusive Suite section. Here, the mid-Cretaceous magmatism from elsewhere in West Antarctica and the adjacent Patagonia and New Zealand is reviewed.

**West Antarctica**

Outside of the Antarctic Peninsula, mid-Cretaceous plutonism is also recognised from other crustal blocks that form West Antarctica (Fig. 1b). Mid-Cretaceous magmatism has been reported from the Thurston Island crustal block (Riley et al., 2017a) and at several locations from the adjacent Marie Byrd Land crustal block (e.g. Siddoway et al., 2005; Korhonen et al., 2012; Kipf et al., 2012).

***Marie Byrd Land***

Marie Byrd Land is divided into two distinct geological provinces (Pankhurst et al., 1998b); the Ross Province in the west and the Amundsen Province in the east. The Amundsen Province is dominated by a Permian to Cretaceous-age batholith that has been correlated with the Antarctic Peninsula batholith (Leat et al., 1995) and also the Median Batholith of New Zealand (Pankhurst et al., 1998b). This potentially continuous belt of magmatism is linked to subduction along the proto-Pacific West Gondwana margin.

Mid-Cretaceous magmatism in Marie Byrd Land is a complicated picture of I-type, A-type, S-type and migmatitic granitoids that range in age from ~130 to 95 Ma (e.g. Kipf et al., 2012) and record a rapid change from purely subduction-related magmatism to rift-related magmatism (Weaver et al., 1994). This event transition correlates with the final stages of subduction of the Phoenix Plate (including the Manihiki Plateau; Hochmuth and Gohl, 2017) and the subsequent rifting of New Zealand from West Antarctica, prior to the opening of the Southern Ocean (Weaver et al., 1994; Siddoway et al., 2005).

Mukasa and Dalziel (2000) dated I-type granitoids (diorite, granodiorite, monzogranite) from Marie Byrd Land in the interval 128 – 96 Ma, although issues with discordant data mean that some of the ages are less well constrained. The ages that were considered more reliable fall in the range 116 – 101 Ma, whilst a suite of migmatites from the Demas Range on the Ruppert Coast (Fig. 1) indicate that migmatization was a protracted process from 128 ± 2 to 113 ± 2 Ma, but with possible peaks at ~127 Ma and ~115 Ma.

Mid-Cretaceous age magmatism associated with crustal anatexis was present in the Fosdick Mountains region of Marie Byrd Land. It was emplaced during the interval 115 – 98 Ma (Siddoway et al., 2005; Korhonen et al., 2010; McFadden et al., 2010; Brown et al., 2016), which was divided into two distinct chronological groups at 115 – 110 Ma and 109 – 102 Ma based on their geochemistry and emplacement depth. However, the data precision was relatively poor and reliability for the interpretation of precise chronology is weak. The two possible events are interpreted to be both linked to crustal anataxis with the older granitoids derived from the Carboniferous-age Ford granodiorite suite, whilst the younger magmatic episode was compositionally more closely related to the pre-Devonian metasedimentary Swanson Formation (Yakymchuk et al., 2013, 2015).

Of direct relevance to this study are the I-type granitoids of Marie Byrd Land, which are interpreted to be directly related to subduction processes along the Gondwana margin (Mukasa and Dalziel, 2000). Calc-alkaline granitoids of granodiorite, quartz diorite and granite composition, combined with foliated granitoids and migmatites indicate three distinct magmatic/metamorphic events at 125, 117 and 105 Ma. This is followed by an abrupt shift to A-type magmatism at ~105 Ma with a suite of syenites and quartz syenites identified from the Ruppert and Hobbs coasts of western Marie Byrd Land (Fig. 1b), which have an overall age range of 107 ± 1 to 98 ± 1 Ma (Storey et al., 1999; Mukasa and Dalziel, 2000).

***Thurston Island***

The Thurston Island crustal block is situated in an intermediate position between the Antarctic Peninsula and Marie Byrd Land (Fig. 1a) and would have occupied a continental margin position during the mid-Cretaceous. Its current position may have been rotated from its Gondwana paleo-position during the Mesozoic (Martin, 2007). Thurston Island has a Late Carboniferous granitic basement with the youngest magmatism recorded during the mid- to late Cretaceous (Riley et al., 2017a) and is of relevance to the discussion in this paper.

Pankhurst et al. (1993) dated (Rb-Sr) an episode of magmatism in the interval 102 – 89 Ma, but urged caution on the reliability of the ages. A more recent study on the U-Pb geochronology of Thurston Island (Riley et al., 2017a) has dated a biotite granite from Lepley Nunatak (Fig. 1b) at 108 ± 1 Ma, but also with inherited grains of ~125 Ma age. The dated granite is part of a wider suite of granitoids on the Eights Coast (Fig. 1b) that are likely to also represent mid-Cretaceous magmatism.

**Patagonia**

The mid-Cretaceous was a period of high magma production across several areas of Patagonia. In the North Patagonian Andes, Pankhurst et al. (1999) reported significant mid-Cretaceous magmatism from the main cordillera of the North Patagonian Batholith (Fig. 1c). This magmatism is synchronous with the volcanic rocks of the Divisadero Group (Suarez et al., 2009) which form almost 1km thickness of silicic tuffs and volcaniclastic rocks. The Divisadero Group (Fig. 1c) is characterised by three distinct pulses of volcanic activity at ~124 Ma, ~117 Ma and 109 – 101 Ma (Pankhurst et al., 2003; Suarez et al., 2009). Volcanic activity in the Divisadero Group is essentially mirrored in the plutonic record of the North Patagonian Batholith (Fig. 1c) where similar pulses of magmatism are recorded, with an emplacement peak at ~118 – 116 Ma. The granitoids are an assemblage of I-type, calc-alkaline plutons and batholiths of granite, tonalite, monzogranite and granodiorite (Pankhurst et al., 1999).

In the Rocas Verdes-Austral basin (Fig. 1a), magmatism of the South Patagonian batholith peaked at ~150 Ma, but continued until at least 80 Ma (Barbeau et al., 2009) and, in part, overlapped with silicic volcanism of the Kachaike Formation (Ghiglione et al., 2015).

Generally speaking, the onset of intense mid-Cretaceous magmatism in North Patagonia is marked by a shift from extension and lithospheric thinning (during the Jurassic) to a period of compression and oroclinal bending in Patagonia and the Antarctic Peninsula (Echaurren et al., 2017). The age distribution of magmatism in the North Patagonia Batholith has been discussed by Pankhurst et al. (1999) and Rapela et al. (2005) who identified significant peaks in emplacement at 124, 118 and 103 Ma, which is akin to the chronology of volcanic activity of the Divisadero Group (e.g. Echaurren et al., 2017). A similar age distribution has been identified in the detrital zircon record of the southern Andes by Paterson and Ducea (2015) who highlighted enhanced magmatism during the mid-Cretaceous and with clear peaks at 126 and 115 Ma, and a lesser peak at 105 Ma.

**New Zealand – Eastern Australia**

Mid-Cretaceous magmatism of the Western Province of New Zealand is recognised in several granitoid suites. The Separation Point and Hohonu batholiths have prolonged geological histories dating back to the Paleozoic, but with the main construction taking place during the mid-Cretaceous (Muir et al., 1994; Waight et al., 1997). The plutons range in composition from tonalite to monzogranite and have an age range of 119 – 110 Ma and were emplaced during a tectonic transition from lithospheric thickening to extension as continental break-up began. Milan et al. (2017) and Decker et al. (2017) have identified a period of enhanced magmatism during the mid-Cretaceous that they have termed a flare-up. During the interval 128 – 114 Ma, more than 90% of the Cretaceous plutonic arc root was emplaced and approximately 70% in the interval 118 – 114 Ma, during an episode of regional transpression.

It is also worth commenting on the extensive mid-Cretaceous magmatism identified further along the Gondwana margin, in southeast Australia as part of the Whitsunday silicic large igneous province, which had a peak in magmatism during the interval 120 – 105 Ma (Bryan et al., 2012).

**GEOCHRONOLOGY**

Fourteen granitoids from a range of localities along the eastern margin of Palmer Land (Fig. 2) have been dated to investigate their emplacement age and their relationship to the key tectonic events of the southern Antarctic Peninsula.

**Analytical procedures**

U-Pb zircon geochronology was carried out using the Cameca IMS 1280 ion microprobe, housed at the NORDSIM isotope facility, Swedish Museum of Natural History (Stockholm).

Zircons, separated by standard heavy liquid procedures were mounted in epoxy and polished to expose their interiors. Approximately 3kg of material was crushed for each sample and zircon was separated from a sieved fraction <500 μm. At least 50 zircon grains were picked from each sample in an attempt to select a broad range of morphologies, although typically ~10 grains were analysed per sample, which were considered representative of the zircon population. They were imaged by optical microscopy and cathodoluminesence (CL) prior to analysis. The CL images were used as guides for analysis targets because they reveal the internal structure of the grains. The analytical methods closely followed those detailed by Whitehouse and Kamber (2005). U/Pb ratio calibration was based on analysis of the Geostandard reference zircon 91500, which has a 206Pb/238U age of 1065.4 ± 0.6 Ma and U and Pb concentrations of 81 and 15 ppm respectively (Wiedenbeck *et al.,* 1995).

Common lead corrections were applied using a modern day average terrestrial common lead composition (207Pb/206Pb = 0.83; Stacey and Kramers, 1975) where significant 204Pb counts were recorded. Age calculations were made using Isoplot v.3.1 (Ludwig, 2003) and the calculation of concordia ages followed the procedure of Ludwig (1998). The results are summarised in Table 1. The uncertainty in the calculated ages is 2/95% confidence limits.

**Sample descriptions and results**

***Intensely deformed granitoids***

Sample R.7183.2 is a strongly foliated hornblende-biotite granodiorite from Mount Schimansky in the Welch Mountains (Fig. 2). Zircon grains from R.7183.2 are typically stubby, prismatic grains with aspect ratios of 2:1 and crystal length of <150 µm. Under CL, the grains often have a rather diffuse character, with shadowy, non-luminescent cores. Nine analyses were carried out on 9 grains and yielded a concordia age of 127.1 ± 0.7 Ma (Fig. 4a) and a 206Pb/238U weighted average age of 127.2 ± 0.7 Ma (MSWD: 2.4). Two analyses were not included in the calculation as one analysis was interpreted to be discordant and another analysis was close to an inclusion and the result was unreliable (Table 1).

Sample R.7180.1 is an intensely deformed LS-tectonite, mylonitized hornblende granodiorite (Fig. 3a) from Mount Schimansky (Welch Mountains) in eastern Palmer Land (Fig. 2). Zircons from R.7180.1 are well-faceted, prismatic grains typically <200 µm in length, but rarely >300 µm. They have aspect ratios of up to 4:1, but are typically more stubby in habit. Under CL, the grains have well-developed outer growth zones, but frequently have more characterless cores (Fig. 5). Nine analyses were carried out on 8 grains and yielded a concordia age of 129.7 ± 0.8 Ma (Fig. 4b) and an identical 206Pb/238U weighted average age. Two analyses were not included in the age calculation (Table 1), with one grain interpreted to be an inherited grain of ~181 Ma, whilst a second analysis was slightly discordant and the analysis spot from close to the edge of the grain.

Sample R.7629.1 is a strongly foliated hornblende-biotite tonalite with mafic enclaves from the Du Toit Mountains (see Vaughan et al., 2012a for detail) of eastern Palmer Land (Fig. 2). Zircons from R.7629.1 are well-faceted, prismatic grains up to 200 µm in length and with aspect ratios of 3:1. Under CL, many of the grains display well-developed growth zones, but often with more featureless, non-luminescent cores (Fig. 4). Ten analyses from 10 separate grains yielded a concordia age of 126.5 ± 0.7 Ma (Fig. 4c) and a 206Pb/238U weighted average age in agreement of 126.5 ± 0.6 Ma (MSWD: 0.58). One analysis was not included in the age calculation as it was interpreted to have been subject to minor Pb loss. No inherited grains were identified in sample R.7629.1. This is a re-analysed sample of that dated by Vaughan et al. (2012a) due to concerns about possible resetting; the 40Ar/39Ar biotite cooling age of Vaughan et al. (2012a) was 116.5 ± 1.5 Ma and can now be considered unreliable as a crystallization age and may even represent a reset age.

***Moderate to strongly deformed granitoids***

Sample P14.25.1 is a hornblende quartz diorite (Fig. 3b) from near Mount Crowell in the RARE Range (Fig. 2); it is medium-grained, has abundant mafic-rich enclaves and is characterised by a pronounced tectonic foliation. Zircons from sample P14.25.1 are well faceted, prismatic grains with cathodoluminesence (CL) images displaying growth. Thirteen analyses were carried out on 10 separate grains and yielded a concordia age of 118.4 ± 1.4 Ma (Fig. 4d) and a 206Pb/238U weighted mean age of 118.3 ± 1.4 Ma. Two analyses were not included in the calculation as they were interpreted to be inherited and gave ages of 180.7 ± 2.9 Ma and 131.2 ± 4.6 Ma (Table 1).

P14.46.1 is a medium grained hornblende tonalite with a well-developed magmatic foliation (Fig. 3c, d) and was sampled from the northwest RARE Range (Fig. 2). Zircons from P14.46.1 are prismatic grains with aspect ratios of 3:1 and maximum grain length of ~150 µm. Under CL the zircon grains are not strongly luminescent and generally have a diffuse character. Thirteen analyses were carried out on 7 separate grains and yielded a concordia age of 119.0 ± 1.3 Ma (Fig. 4e) and an identical 206Pb/238U weighted average age of 119.0 ± 1.3 Ma (MSWD: 0.39). Six analyses were not included in the age calculation as four were interpreted to have suffered recent Pb loss (Fig. 4e; Table 1) and two further analyses were interpreted to be inherited grains with an age of ~234 Ma (Table 1).

Sample R.7614.1 from Hagerty Peak near the Witte Nunataks in southern Palmer Land (Fig. 2) is a medium-grained, leucocratic biotite-hornblende granodiorite, but also varying to quartz monzodiorite. The granitoid has a well-developed tectonic foliation which is parallel to the cleavage in the host sedimentary rocks. Zircons from sample R.7614.1 are large prismatic grains up to 250 µm in length and aspect rations of 3:1. Under Cl, the grains are moderately luminescent, but generally have a diffuse character, although concentric growth zones are still evident. Ten analyses were carried out on 9 separate grains and yielded a concordia age of 115.9 ± 0.7 Ma (Fig. 4f) and an identical 206Pb/238U weighted average age. Three analyses were not included in the final age calculation; one had minor recent Pb loss and two more were slightly discordant (Fig. 4f). However, including all 10 analyses leads to an indistinguishable concordia age of 115.8 ± 0.9 Ma (MSWD: 1.8). A sample from the same pluton was also dated by Rowley et al. (1988), and Pankhurst and Rowley (1991) using K-Ar and Rb-Sr methods respectively. They recorded ages consistent with this study of between 116 – 112 Ma.

***Weakly deformed granitoids***

Sample P14.35.1 is a weakly foliated, medium-grained hornblende tonalite from the western RARE Range (Fig. 2). It is characterised by abundant micro (<5cm) mafic enclaves and minor copper mineralization. Zircons from P14.35.1 are generally well-faceted, prismatic grains with aspect ratios of 3:1 and typically 150 – 200 µm in length. Under CL, the grains often have much darker, featureless cores and rims with well-developed growth zones due to variations in rare earth element concentrations (Fig. 5). The darker cores do not show any compositional differences inU or Th to the outer parts of the zircons grains. Fifteen analyses were performed on 11 separate grains and yielded a concordia age of 117.9 ± 1.3 Ma (Fig. 4g) and a 206Pb/238U weighted average age of 117.1 ± 1.2 Ma (MSWD: 0.97). One analysis was not included in the age calculation as it was interpreted to represent an inherited grain with an age of ~125 Ma.

Sample R.8264A.1 is a medium-grained hornblende granodiorite with abundant mafic enclaves from Galan Ridge in the Mosby Glacier area (Fig. 2). Zircons separated from R.8264A.1 are prismatic and broken grains with aspect ratios of 3:1 and a maximum length of 200 µm. Under CL, most grains exhibit well-developed growth zoning patterns (Fig. 5) and are strongly luminescent. Ten analyses were carried out on 8 separate grains and yielded a concordia age of 113.4 ± 0.8 Ma (Fig. 4h) and a consistent 206Pb/238U weighted average age of 113.7 ± 0.7 Ma (MSWD: 2.0). Four analyses were not included in the age calculation (Table 1), with one grain interpreted to be inherited with a ~178 Ma core and a ~121 Ma rim. A third analysis, also not included in the age calculation, was tentatively interpreted to be inherited with an age of ~118 Ma (Fig. 4h) based on the tight cluster of analyses at ~113 Ma, although clearly still related to LCIS magmatism. A fourth analysis was slightly discordant and also not included in the age calculation.

Sample R.8266A.1 is a leucocratic hornblende-biotite granodiorite from Galan Ridge, close to the Mosby Glacier (Fig. 2) and adjacent to the pluton sampled at site R.8264A.1. Zircons from R.8266A.1 are prismatic and broken grains occasionally up to 250 µm in length, but typically ~150 µm, with aspect rations of 3:1. Under CL, the grains are strongly luminescent and occasionally preserve well developed growth zones. Ten analyses from 10 separate grains yielded a concordia age of 112.6 ± 0.6 Ma (Fig. 4i) and an identical 206Pb/238U weighted average age (MSWD: 2.3). One analysis was not included in the final age calculation as it was interpreted to be an inherited grain with an age of 127 Ma (Table 1).

***Undeformed granitoids***

Sample P14.3.1 is an unfoliated, megacrystic biotite granite from the western Copper Nunataks region (Fig. 2). Zircons from P14.3.1 are well faceted, prismatic grains (~150 µm length), typically with aspect ratios of 3:1, but rarer, more acicular grains also occur. CL images (Fig. 5) reveal well-preserved growth zoning. Fourteen analyses were carried out on 10 separate grains (prismatic and acicular) and yielded a concordia age of 117.1 ± 1.3 Ma (Fig. 4j) and a 206Pb/238U weighted mean age of 117.2 ± 1.3 Ma (MSWD: 0.35). No inherited grains were identified in sample P14.3.1.

P14.11.1 is an unfoliated, megacrystic biotite granite (Fig. 3e) from the western Copper Nunataks region (Fig. 2). Zircons from P14.11.1 are a mix of large (200 µm), stubby (3:1 aspect ratio), prismatic grains, preserving well developed growth zoning under CL, although some grains are more featureless. Twelve analyses were carried out on 7 grains and yielded a concordia age of 102.5 ± 0.6 Ma (Fig. 4k) and a 206Pb/238U weighted mean age of 102.3 ± 1.2 Ma (MSWD: 1.2).

Sample P14.103.1 is an unfoliated medium-grained hornblende tonalite-granodiorite (Fig. 3f) from the southern Hutton Mountains (Fig. 2). Zircons from P14.103.1 are well faceted, prismatic grains with aspect ratios of up to 5:1 and individual grains >200 µm in length (Fig. 5). The zircon grains often preserve well developed growth zones, although the core is sometimes more characterless (Fig. 5). Fourteen analyses were carried out on 10 separate grains and yielded a concordia age of 106.5 ± 1.4 Ma (Fig. 4l) and a 206Pb/238U weighted mean age of 106.4 ± 1.0 Ma (MSWD: 0.87).

Sample P14.138.1 is a hornblende-rich, medium-grained quartz diorite (Fig. 3g, h) from the western Hutton Mountains (Fig. 2). It has no evidence for any magmatic or tectonic foliation. Zircon grains from P14.138.1 are generally stubby, prismatic grains with length <150 µm and aspect ratios of <3:1. Under CL, the grains are generally characterised by dark featureless cores and growth zones are occasionally evident in the outer parts of the grains. Twelve analyses were carried out on 8 grains and yielded a concordia age of 103.9 ± 1.4 Ma (Fig. 4m) and a 206Pb/238U weighted mean age of 103.6 ± 1.3 Ma (MSWD: 0.40). Four analyses were not included in the age calculation; three were identified as inherited grains with ages of 119, 188 and 1109 Ma (Table 1). The 1109 Ma age is recorded from a distinctive, rounded core which is dark under CL. A fourth analysis was excluded as it was close to the edge of a zircon grain and there was uncertainty regarding the reliability of the analysis.

Sample N10.413.1 is a coarsely crystalline diorite with biotite clusters from Krebs Ridge on the Eileson Peninsula (Fig. 2). The diorite shows no evidence of any magmatic or tectonic foliation. Zircons from N10.413.1 are prismatic grains with aspect ratios of 4:1 and individual grains up to 200 µm in length. Under CL, many of the grains show growth zoning, although the cores are often darker and featureless and the very outer rims are strongly luminescent. Ten analyses were carried out on 9 grains and yielded a concordia age of 117.7 ± 0.6 Ma (Fig. 4n) and an identical 206Pb/238U weighted average age. One analysis was not included in the age calculation due to minor Pb loss (Fig. 4n).

**AGE SUMMARY**

This current study presents the first comprehensive analysis of the age of the Lassiter Coast intrusive suite (LCIS) of the southern Antarctic Peninsula. Previous studies (e.g. Pankhurst and Rowley, 1991; Flowerdew et al., 2005; Vaughan et al., 2012a) have demonstrated that the magmatism of the LCIS marks a significant event during the mid-Cretaceous and was also widespread around the margins of the paleo-Pacific basin (Vaughan and Livermore, 2005). Previous age estimates of the LCIS fall in the range, 119 – 95 Ma, with a peak of emplacement in the interval 110 – 100 Ma. These age ranges are however largely based on Rb-Sr and K-Ar geochronology, which are sometimes found to be susceptible to resetting following deformation and associated metamorphism. Although it should be noted that many of the whole rock and mineral separate Rb-Sr and K-Ar ages are accurately recording the emplacement age of plutonism.

The age range identified from this study, combined with the high precision ages from Flowerdew et al. (2005) and Vaughan et al. (2002) fall in the interval 130 – 103 Ma. The cumulative frequency curve and histogram of these data (163 U-Pb analyses from 18 samples) are plotted in Fig. 6a and highlight the presence of three distinct episodes of magmatism across the entire LCIS. The three peaks of emplacement occur at 130 – 126 Ma (P1), 118 – 115 Ma (P2) and 107 – 103 Ma (P3) with clear lulls in magmatism between P1-P2 and P2-P3 (Fig. 6a).

The LCIS age data discussed in Vaughan et al. (2012b) includes ~40 previously published emplacement ages from eastern Palmer Land. Vaughan et al. (2012b) only used Rb-Sr and K-Ar mineral ages (taken from Mehnert et al. (1975); Farrar and Rowley (1980); Farrar et al. (1982); Pankhurst and Rowley (1991)) that they considered to be reliable and excluded those that may have experienced post-crystallization perturbations. A combined cumulative frequency curve and histogram for the U-Pb data from this study, Vaughan et al. (2002), Flowerdew et al. (2005), 40Ar/39Ar data from Vaughan et al. (2012a), alongside the K-Ar and Rb-Sr ages collated by Vaughan et al. (2012b) are plotted in Fig. 6b. In this combined dataset (208 points) the three magmatic peaks remain distinct, but with a slightly more enhanced peak for the P3 magmatism and a peak age range of 108 – 102 Ma. In both figures there is a slight shoulder on the P2 peak, reflecting a potential event at ~114 – 113 Ma, which maybe distinct to the major 118 – 117 Ma peak or represent a slightly longer duration event of 118 – 113 Ma or a sampling bias. The P1 magmatic event is apparently a more restricted episode of pluton emplacement compared to the other two events and is largely restricted to the more northern parts of the LCIS (Fig. 2).

There is very little evidence of inheritance in any of the granitoids of the LCIS, which may imply higher temperatures (~850 ˚C) during granitoid petrogenensis at lower crustal depths (c.f. Miller et al., 2003). In sample P14.46.1, two grains have recorded ages of ~234 Ma (Table 1; not shown in Fig. 6a) and reflect a widespread Triassic magmatic event in West Antarctica; magmatism in the interval 240 – 220 Ma is well recognised in the southern Antarctic Peninsula (Millar et al., 2002; Flowerdew et al., 2006; Riley et al., 2012). Triassic-age magmatism is also known from the Walgreen Coast of Marie Byrd Land (Pankhurst et al., 1998; Mukasa and Dalziel, 2000) and from Thurston Island granitoids (239 ± 4 Ma; Riley et al., 2017a).

The only other significant occurrence of zircon inheritance is observed in four of the dated samples, which record the presence of a ~180 Ma magmatic event. This reflects an episode of Early Jurassic magmatism that was widespread in the southern and central Antarctic Peninsula (Riley et al., 2017b). This magmatic event forms the local crystalline basement of eastern Palmer Land and is characterized by moderate to strongly foliated granitoids which have been dated in the interval, 188 – 181 Ma (Riley et al., 2017b) and overlap with magmatism of the Subcordilleran plutonic belt of Patagonia (185 – 181 Ma; Rapela et al., 2005). The Early Jurassic plutons of Palmer Land were interpreted to not represent the sub-volcanic equivalent of the 187 – 182 Ma silicic ignimbrites and tuffs of the Mount Poster and Brennecke formations of southern Palmer Land (Pankhurst et al., 1998a; Riley et al., 2001). The volcanic rocks of the southern Antarctic Peninsula are part of the wider V1 silicic volcanism of the Patagonia-West Antarctica Chon Aike Province (Pankhurst et al., 2000).

**CORRELATIONS ALONG THE PACIFIC-MARGIN OF GONDWANA**

Mid-Cretaceous magmatism of the North Patagonia Andes, the West Antarctic margin of Marie Byrd Land and Thurston Island, and to some extent, the Western Province of New Zealand all share a common magmatic history with that of the Antarctic Peninsula.

The three distinct magmatic peaks (Fig. 6b) identified in this study are also observed in the North Patagonia Batholith and the Divisadero Group volcanic rocks of the North Patagonian Andes. The North Patagonia Batholith has a much longer magmatic history that extends from at least the Permian until the Cenozoic, but also with a peak of plutonic magmatic activity during the Aptian – Albian (Echaurren et al., 2017). During this peak in magmatism there are three distinct episodes at 124, 118 and 103 Ma (Echaurren et al., 2017), which are mirrored in the volcanic Divisadero Group (124, 117 and 109 – 101 Ma; Pankhurst et al., 1999, 2003).

In Marie Byrd Land of West Antarctica (Fig. 1b), the mid-Cretaceous magmatic history is a little more complicated and records a shift from I-type granitoids associated with the subduction of the Phoenix Plate and coeval S-type granitoids, to A-type syenites and alkali granites associated with the rifting and separation of New Zealand from West Antarctica (e.g. Korhonen et al., 2010). However, there is still a clear emergence of three distinct age peaks of I- and S-type, subduction-related magmatism and migmatization at 125, 117 and 105 Ma (Mukasa and Dalziel; Siddoway et al., 2005; Korhonen et al., 2010; Kipf et al., 2012; Brown et al., 2016). The data from these sources are plotted in the cumulative frequency curve and histogram in Fig. 5c and also demonstrates clear episodicity during the mid-Cretaceous, even with a far smaller dataset. In Marie Byrd Land, four distinct events are recognised, including a separate event at ~133 Ma (Fig. 6c).

The neighbouring Thurston Island crustal block of West Antarctica (Fig. 1a) has limited rock outcrop, but preserves plutonic rocks of 108 Ma age with inherited grains of ~125 Ma (Riley et al., 2017a) corresponding to the P1 and P3 events of the LCIS magmatism. The older ages are confirmed by Pankhurst et al. (1993) who identified plutonic rocks on Thurston Island in the interval 127 – 121 Ma, using Rb-Sr dating methods.

Geochronology from the Western Province of South Island, New Zealand also highlights a period of significant mid-Cretaceous magmatism with a peak of emplacement from 119 – 114 Ma and a second episode from 110 – 101 Ma (Muir et al., 1994, 1997; Waight et al., 1998; Decker et al., 2017; Milan et al., 2017).

A clear picture has emerged of, not just, an episode of enhanced mid-Cretaceous magmatism along the West Gondwana margin, but of Aptian – Albian pluton emplacement and minor volcanism with three distinct age peaks. Although there are clearly minor differences along the length of the Cordillera margin, peaks at ~128, ~116 and ~105 Ma are evident from this study and other recent high precision geochronology studies.

**RELATIONSHIPS TO MID-CRETACEOUS DEFORMATION**

The mid-Cretaceous is well recognised (e.g. Vaughan and Livermore, 2005, Matthews et al. 2012) as a period of Pacific plate reorganization and widespread but short-lived intense deformation, alongside enhanced magmatism (LIPs and continental margin).

Along the West Gondwana margin, mid-Cretaceous deformation is widespread from Patagonia to Marie Byrd Land (Vaughan et al., 2012b) and into New Zealand (Bradshaw, 1993). The geodynamic setting of the Antarctic Peninsula in the mid-Cretaceous was one of transpressional deformation, broadly termed the Palmer Land Event (Vaughan et al., 2012b). . The event has previously been associated with the accretion of allocthonous terranes to the Gondwana margin (Vaughan and Pankhurst, 2000), but this has been challenged by Burton-Johnson and Riley (2015) who favour an in-situ arc development model. Contemporaneous deformation along the length of the West Gondwana margin (e.g. New Zealand), implies that the deformation recorded on the Antarctic Peninsula is a local expression of a potentially global tectonically-driven deformation event (Matthews et al, 2012). Whatever its cause, the Palmer Land Event’s deformation history is recorded in the eastern Palmer Land shear zone (Fig. 2), which is a major ductile to brittle-ductile shear zone. Its extent is thought to be at least 1500 km and it’s up to 20 km wide in places (Vaughan and Storey, 2000). The emplacement of the LCIS was synchronous with the Palmer Land Event and the deformation history recorded in the mid-Cretaceous granitoids has been used by Vaughan et al. (2012a, 2012b) to demonstrate two distinct tectonic events. Phase 1 of the Palmer Land Event occurred between 116 and 107 Ma and may even have started prior to 120 Ma, and was primarily a compressional event controlled by sinistral transpression (Vaughan et al., 2012a). Phase 1 concluded with the development of a mylonite fabric prior to the onset of Phase 2 of the Palmer Land Event. Phase 2 occurred at ~103 Ma and was a more restricted compressional event compared to Phase 1.

Evidence from this study supports the conclusions of Vaughan et al. (2012a) that the LCIS was emplaced during a prolonged phase of compression. Fig. 7 illustrates structural data from across the LCIS for pre-, syn- and post-magmatic scenarios. The pre-magmatic data is recorded from the host sedimentary rocks (Latady Formation; Fig. 2), which indicate WNW-ESE tectonic compression, whilst the syn-magmatic regime is illustrated using mafic enclave foliations in the plutons. The enclaves also indicate continued WNW-ESE compression, as do the mafic dykes that cross-cut the LCIS granitoids, indicating post-LCIS compression. However, the comprehensive geochronology dataset that forms the basis of this study demonstrates that the tectonic model of Vaughan et al. (2012a) requires updating, particularly the timing and duration of tectonic events and magmatism. The key points from this study are that the P1 granitoids are all intensely deformed LS-tectonites which show high-strain features and development of mylonite. This tectonic fabric is also present in the host sedimentary rocks of the Latady Formation where it is developed as a penetrative and planar cleavage. This suggests the emplacement of the P1 granitoids was coincident with the high-strain sinistral transpression phase 1 of the Palmer Land Event; indicating that the Palmer Land Event extends to at least 130 Ma and was intensely developed leading to a penetrative foliation in the granitoids.

The P2 granitoids (118 – 113 Ma) are more varied in terms of their deformation fabrics, exhibiting a well-developed foliation in the older group and moderate to weak foliation in the younger group (<114 Ma). The enclave data from the P2 granitoids indicate that their emplacement still took place under a compressive regime, but less intense than during the P1 emplacement. The P3 granitoids dated as part of this study do not show any evidence for the development of a tectonic, and often no magmatic fabric. The structural data from the post-plutonic dykes (Fig. 7) indicates that the compressive regime was ongoing, but at the time of P3 emplacement was very localized (Vaughan et al., 2012a) or had ended. The 40Ar/39Ar dates obtained by Vaughan et al. (2012a; 2012b) and used to pinpoint the two tectonic phases of the Palmer Land Event are called into question on the basis of the pluton ages determined here. This also has implications for the significance of the subduction of the Manihiki Plateau for triggering the Palmer Land Event as suggested by Hochmuth and Gohl (2017).

The intensely deformed tonalite, R.7629.1, from the Du Toit Mountains (Fig. 2) that was dated as part of this study was also dated by Vaughan et al. (2012a) who recorded an 40Ar/39Ar biotite cooling age of 116.5 ± 1.5 Ma (MSWD: 1.1) which they interpreted as the age of crystallization. The newly acquired date of 126.5 ± 0.7 Ma indicates that crystallization was 10 Myr earlier and that the 116.5 ± 1.5 Ma age is likely to represent a reset age related to a later deformation or intrusive event. The tectonic fabric of the Du Toit Mountains tonalite was interpreted by Vaughan et al. (2012a) to be consistent with syn-magmatic deformation during pluton cooling. This therefore indicates that the Palmer Land compressional event was ongoing at ~130 Ma and continued until ~116 Ma before waning.

The absence of a tectonic fabric in any of the P3 granitoids dated here also indicates that the Phase 2 of the Palmer Land Event (Vaughan et al., 2012b) was either very localised (Vaughan et al., 2012a) or had essentially ceased by ~107 Ma. The significant peak for the P3 magmatic event (Fig. 6b) also indicates that phase 2 (~103 Ma) of the Palmer Land Event did not suppress pluton emplacement as suggested by Vaughan et al. (2012b).

**FLARE-UP EVENTS ALONG CONTINENTAL MARGINS**

Long-lived continental margin arcs are characterised by periods of magmatic episodicity and high magma addition rates (MARs) or flare-ups (de Celles et al., 2009). Milan et al. (2017) quantified flare-up conditions based on magma flux volumes; with ‘normal’ continental margin conditions leading to a magma flux rate of 14km3/Myr per km of arc, whilst flare-up conditions have values of 100-150km3/Myr per km of arc, dependent upon crustal thickness conditions at the time. These events appear to be margin-wide, but episodicity at much shorter durations has also been documented on the scale of individual batholiths (e.g. da Silva and Gosnold, 2007; Milan et al., 2017) and may even be fractal over four spatial scales (de Silva et al., 2015). A compilation of detrital zircon age data from the Southern Andes of Patagonia is shown in Fig. 8 (Paterson and Ducea, 2015) and illustrates the magmatic flare-ups and lulls during the last 400 Myr with magmatic peaks occurring during the mid-Cretaceous, Middle Jurassic and the Permian.

High MAR episodes typically last 5 – 20 Myr (e.g. Best et al., 2016), which alternate with longer periods of 30 – 70 Myr of low-MAR episodes (de Celles et al., 2009). It is within the period of a high-MAR episode that is the focus of this study and that within that episode, we also see a secondary pattern of flare-ups and lulls during the interval, 130 – 102 Ma. The second-order episodicity identified within the mid-Cretaceous flare-up is evident throughout Patagonia (e.g. Echaurren et al., 2017), the Antarctic Peninsula (this study), Marie Byrd Land (e.g. Mukasa and Dalziel, 2000), Thurston Island (Riley et al., 2017) and to some extent, New Zealand (e.g. Decker et al., 2017), with high MAR events at 130 – 126 Ma, 118 – 113 Ma, 108 – 102 Ma and clear lulls in between (Fig. 6). Second-order episodicity within a broader magmatic flare-up has been suggested by de Silva et al. (2015) who considered that secondary pulses can be defined on a regional spatial scale with magmatism forming clear ‘nodes’. The second-order pulses of <6 Myr duration reflect the timescale of melt production and transport from the lower crust (Fig. 9) and require a significant component of the arc magma to be derived from melt-fertile lower crust (Milan et al., 2017).

Riley et al. (2016) have investigated the geochemistry of several suites of mafic rocks in eastern Palmer Land and identified that significant lithospheric thinning occurred as a direct consequence of the extensive melting associated with the emplacement of the LCIS. On a Peninsula-wide scale, the emplacement of the LCIS marks a major magmatic flare-up and one that is seen extensively along the West Gondwana margin during the Aptian – Albian. It follows a Middle Jurassic flare-up event at ~170 Ma (Riley et al., 2001) and the time interval between these two events is consistent with the work of de Celles et al. (2009) who suggested intervals of 30 – 70 Myr between high MAR events.

Continental margin flare-ups are interpreted to be related to the upper plate tectonic regime and are typically associated with mafic underplating and initial lithospheric thickening (Paterson and Ducea, 2015) or plume-lithosphere interaction (e.g. Vaughan, 1995). High-flux episodes require a significant component of arc magmatism to be derived from melt fertile lower crust. The North and South American Cordillera flare-ups have been attributed to the under-thrusting of a melt fertile lower crustal foreland into the base of the arc (Ducea and Barton ,2007; De Celles et al., 2009). Whilst the New Zealand Cordillera flare-up is attributed to the under-thrusting and subsequent melting of foreland Gondwana margin crust. Both models indicate the importance of developing a highly fusible regime.

The primary and second order episodicity observed on the West Gondwana margin is likely to be more strongly aligned to the development and depletion of a lower crustal fusible layer. On a global scale, the mid-Cretaceous flare-up was associated with accelerated plate motions (e.g. South Atlantic spreading and plate reorganisation in the paleo-Pacific basin as well as the widespread development of oceanic and continental LIPs.

**EXTENSION-RELATED FLARE-UPS**

Enhanced magmatism in continental margin settings is not always directly related to ongoing subduction (e.g. Bryan and Ferrari, 2013) in a compressional regime. The Chon Aike silicic large igneous province of the Early – Middle Jurassic outcrops extensively across the eastern Antarctic Peninsula and Patagonia and is characterized by three distinct magmatic peaks at ~185, 170 and 155 Ma (Pankhurst et al., 2000). The emplacement of ~0.5 million km3 of rhyolitic ignimbrites and crystal-lithic tuffs, and associated sub-volcanic complexes is interpreted to be related to the early break-up of Gondwana, Weddell Sea rifting and influence of the Karoo mantle plume (e.g. Riley et al., 2001).

Given the proximity of the LCIS to the developing Weddell Sea basin (Fig. 1a), the influence of extension in this sector of the developing margin must also be considered when interpreting the LCIS magmatism. Early – Middle Jurassic rifting between the Antarctic Peninsula and South America, along with rifting in the developing Weddell Sea (Jokat and Herter, 2016) lead to Chon Aike silicic magmatism and basaltic magmatism in the Weddell Sea (Jordan et al., 2017) and the eastern Antarctic Peninsula (Riley et al., 2003; 2016). However, by the Early Cretaceous, the crustal blocks of West Antarctica had formed a more linear proto-Pacific continental margin and rifting in the southern Weddell Sea has essentially ceased (Jokat and Herter, 2016). Therefore during the period of LCIS magmatism from 130 – 102 Ma there was no significant extension in the southern Weddell Sea that could have led to onshore magmatism. Combined with a long-lived compressive regime during the mid-Cretaceous (Fig. 7), a subduction origin for the LCIS is favoured and is consistent with the South America-Marie Byrd Land-Thurston Island-New Zealand cordillera.

**CONCLUSIONS**

1. The Lassiter Coast intrusive suite (LCIS) is a voluminous suite of plutons and batholiths that crop out over an area of 80,000 km2. The intrusive rocks are all granitoids, dominated by tonalite, quartz diorite and granodiorite.

2. The West Gondwana margin, including the Antarctic Peninsula, Patagonia, Marie Byrd Land, Thurston Island and New Zealand is marked by several episodes of high magma addition pulses (e.g. Permian, Early – Middle Jurassic and mid-Cretaceous). Within each major flare-up episode a second order of episodicity is recognized that reflect the timescale of melt production and transport from the melt-fertile lower crust.

3. New U-Pb data presented here has identified that the duration of the LCIS was from 130 to 102 Ma and was punctuated by three distinct flare-ups at 130 – 126 Ma, 118 – 113 Ma and 108 – 102 Ma. Between each flare-up episode there is a clear lull in magma addition with a duration of 5 – 8 Myr. There is an implication for the onset and duration of the Palmer Land compressional tectonic event, which must have initiated by 130 Ma and may have continued until ~116 Ma. The later phase of the Palmer Land Event was localized and potentially ended by ~107 Ma, such that the younger granitoids are undeformed.

4. A very similar pattern of magma addition peaks and lulls is identified elsewhere along the West Gondwana margin, particularly in Patagonia (North Patagonia Batholith), Marie Byrd Land and Thurston Island of West Antarctica, and also New Zealand. Again, three clear peaks are identifiable within the margin-wide flare-up.

5. A flare-up episode requires the development of a layer of highly fusible melt fertile zone in the lower crust/upper plate regime as well as a magmatic trigger. This would be the result of extensive underplating of amphibolite dominated material in the lower crust. The catalyst for the melting events are likely to be external (tectonic) driven and related to plate reorganization or plume-lithosphere interaction.

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# List of Figures

# Fig. 1: (a) Reconstruction of the West Gondwana margin at approximately 130 Ma (Martin et al., 2007) showing the location of the Lassiter Coast intrusive suite granitoids. PAT: Patagonia; TI: Thurston Island; MBL: Marie Byrd Land; AP: Antarctic Peninsula; MAD: Madagascar; NZ: New Zealand; FPB: Falkland Plateau Bank; FG: Filchner Graben; EWM: Ellsworth-Whitmore Mountains; RVB: Rocas-Verdes Basin; SJB: San Jorge Basin; FI: Falkland Islands; MB: Malvinas Basin; LCIS: Lassiter Coast Intrusive Suite. The position of key magnetic anomalies are shown (e.g. M10); (b) Map of Antarctica showing the main domains of West Antarctica and the location of principal locations on Thurston Island and Marie Byrd Land.; (c) Map of southern South America (after Pankhurst et al., 2000) showing the extent of Chon Aike volcanic rocks, the Patagonian batholith and the Early Jurassic Subcordilleran plutonic belt. Approximate age of magnetic anomalies: M10 (131 Ma), M19 (140 Ma), M29 (155 Ma).

Fig. 2: Map of the southern Antarctic Peninsula (Palmer Land) showing the extent of the mid-Cretaceous Lassiter Coast intrusive suite and the location of the samples analyzed as part of this study. EPSLZ: Easter Palmer Land shear zone; WB: putative extent of the Werner Batholith

Fig. 3 Outcrop images of granitoids from the Lassiter Coast intrusive suite. a) R.7180.1: zones of grain size reduction are consistent with mylonite formation in brittle/ductile shear zone; b) P14.25.1: quartz diorite with a pronounced tectonic foliation; c) P14.46.1: medium grained tonalite with a pronounced magmatic foliation; d) P14.46.1: medium grained tonalite syn-magmatic foliated enclave cross cut by an aplite dyke; e) P14.11.1: unfoliated megacrystic granite; f) P14.103.1: tonalite-granodiorite with abundant mafic enclavese) f); g) P14.138.1: hornblende-rich medium grained quartz diorite; h) P14.138.1: hornblende-rich medium grained quartz diorite with sub rounded mafic enclaves.

Fig. 4: Concordia diagrams for analyzed zircon grains from granitoids of the Lassiter Coast intrusive suite, Antarctic Peninsula. Dashed ellipses are not included in the age calculation and the bold ellipse is the calculated age. (a) R.7183.2 granodiorite from Mount Schminasky; (b) R.7180.1 granodiorite from Mount Schminasky; (c) R.7629.1 tonalite from the Du Toit Mountains; (d) P14.25.1 quartz diorite from Mount Crowell; (e) P14.46.1 tonalite from the RARE Range; (f) R.7614.1 granodiorite from Hagerty Peak; (g) P14.35.1 tonalite from the RARE Range; (h) R.8264A.1 granodiorite from Galan Ridge; (i) R.8266A.1 granodiorite from Galan Ridge; (j) P14.3.1 tonalite from Copper Nunataks; (k) P14.11.1 granite from Copper Nunataks; (l) P14.103.1 granodiorite from Hutton Mountains; (m) P14.138.1 quartz diorite from the Hutton Mountains; (n) N10.413.1 diorite from Eileson Peninsula.

Figure 5: Representative cathodoluminescence images of analyzed zircon grains from granitoids of the Lassiter Coast intrusive suite. Circles indicate the position of analysis. (a) P14.3.1 Copper Nunataks; (b) P14.103.1 Hutton Mountains; (c) R.7629.1 Du Toit Mountains; (d) R.7180.1 Mount Schimansky; (e) P14.35.1 RARE Range; (f) R.8264A.1 Galan Ridge.

Fig. 6: (a) Age histograms and cumulative frequency curves for the age of granitoids from the Lassiter Coast intrusive suite highlighting the episodicity of the mid-Cretaceous magmatic event. Data sources: U-Pb data (this study, Flowerdew et al., (2005); Vaughan et al., (2002; 2012b). (b) Age histogram and cumulative frequency curve for the Lassiter Coast intrusive suite granitoids. Data sources: as above, plus reliable K-Ar and Rb-Sr data compiled in Vaughan et al. (2012b). (c) Age histogram and cumulative frequency curve for mid-Cretaceous granitoids from Marie Byrd Land. Data sources: U-Pb data (Mukasa and Dalziel, (2000); Korhonen et al. (2010); Kipf et al., (2012); Brown et al. (2016).

Fig. 7: Compiled structural data for the Lassiter Coast, showing: (a) WNW-ESE tectonic compression preceding LCIS emplacement, as recorded by the poles to the tilted bedding of the Latady Formation host rocks; (b) syn-emplacement WNW-ESE compression as recorded by the poles to the mafic enclave foliations in the P1 and P2 plutons; and (c) WNW-ESE tectonic compression post-dating LCIS emplacement, as recorded by the mafic dykes cross-cutting the plutons.

Fig. 8: Age histogram and cumulative frequency curve for detrital zircon data from the southern Andes of Patagonia highlighting the first order episodicity throughout the Phanerozoic (Paterson and Ducea, 2015).

Fig. 9: Flare-up conditions in the arc magmatic system of the crust highlighting the prominent development of a deep crustal melt fertile zone and development and transport of intermediate to felsic melts/batholiths (de Silva et al., 2015).